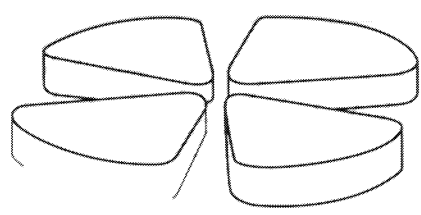


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WORLD TRENDS IN CYCLOTRON DEVELOPMENTS FOR NUCLEAR PHYSICS AND APPLICATIONS

E. Baron

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WORLD TRENDS IN CYCLOTRON DEVELOPMENTS FOR NUCLEAR PHYSICS AND APPLICATIONS

E Baron
GANIL, BP 55027, 14076 Caen Cedex 5, France
Tel 33 2 31 45 45 13 E-Mail baron@ganil.fr

Abstract

Today, the number of cyclotrons operating in the world largely exceeds 200. The field of uses covers production of radioisotopes for medicine, therapy by neutron and ion beams, nuclear, atomic and solid state physics research, material analysis and radiation damage studies, and production of intense neutron beams for present and future purposes. Despite this diversity, continuing efforts driven by both research laboratories as well as commercial firms result in a series of improvements in the various techniques used in the design and operation of cyclotrons. This paper intends to draw the main directions of evolution in the following issues: injection and extraction systems, beam dynamics (including high intensity issues), magnetic and electric fields computation, as well as existing and possible future applications in medicine, production of energy, neutron spallation sources and transmutation technologies. The question of a possible resurrection of Fixed Field, Alternating Gradient cyclotrons (FFAG), a concept invented in the fifties, will be shortly brought up.

1. INTRODUCTION

In order to apprehend the trends in the cyclotron developments, it may be useful to have a quick glance on the past.

The concept of the cyclotron was invented at Berkeley in 1929-1930. The first goal was the acceleration of nuclei used as projectiles to collide with other nuclei, but very soon, the idea of using the neutrons issued from these collisions was advanced. Since then, a wide variety of cyclotrons were built as ideas to improve their capabilities came up. After the evidence that, with flat pole tips, the energy to be given to the projectiles was limited by the discrepancy between the relativistic increase of mass and the synchronism with the fixed frequency of the accelerating field, the idea of modulating this frequency according to this effect was proposed in 1945, it gave birth to the synchrocyclotron. In 1960, 18 synchrocyclotrons were built and allowed acceleration of light particles (p, d, alpha) up to several hundred of MeV, but at the price of abandoning the CW character of the cyclotron. Nevertheless, previous to the second World War, in 1938, L.H. Thomas had proposed an azimuthally varying field to keep the particles and the accelerating field in resonance and to provide vertical focusing at the same time, but his paper was ignored, the idea reappeared in 1950-1952, next to the announcement of the alternating gradient principle. Two electron models were built at Berkeley, but the results which were classified were not known until 1956, and it is only in 1958 that the first isochronous proton cyclotron was built and operated at Delft in the Netherlands. A large number of such cyclotrons were then built with straight or spiralled sectors until again, the limitation of the vertical focussing force showed to be a limit for the maximum energy. The new concept of separated sector cyclotrons came around 1963 and soon, laboratories at Zürich, Bloomington and Vancouver had plans for high energy proton machines. It is also in this period (1975) that the International Conferences on Cyclotrons began to add 'and Their Applications' to their contents, including biology, medicine, chemistry and engineering. By 1973, the bold idea of using superconducting coils came up, thus drastically reducing the overall size (and operation cost) of the magnet. In 1985, both Chalk River and MSU had such

machines in operation, and the latter used an axial injection from an ECR source, another development that would greatly improve the capabilities of cyclotrons. These compact “superconducting cyclotrons” have a return yoke that completely surrounds the vacuum chamber and it seems that the idea was borrowed by the Louvain-la-Neuve accelerator physicists for the construction of room-temperature, fixed frequency cyclotrons which are now commercialised either as isotope producers, or as machines for therapy by proton beams. There is in principle no limit to the maximum energy attainable with a cyclotron, except for the fact that the volume of iron becomes prohibitive. Still, some projects exist to deliver 1 GeV of high intensity proton beams.

It is seen from this short historical survey that the cyclotron has followed a continuous trend of amelioration and applications, and the rest of this paper will now present a sharper analysis of the current progress from the technical point of view as well as in the various fields of application.

2. REQUIREMENTS AND GOALS

Before going into the investigation on the various trends of the techniques and applications of the cyclotron, it is useful to have a clear idea on what is expected from the cyclotron in any possible direction.

Looking at what was the first historical field, nuclear physics, one is expecting nowadays a machine that is very versatile both in terms of energy and of type of projectile, whether stable or radioactive. This leads to require a good transmission efficiency from source to target: a radioactive beam will in general be of tiny intensity and therefore each ion is precious, while for stable beams, the need is generally for high intensities, and it is a must to minimise the losses, at least inside the vacuum chamber and at extraction.

Medical applications may be split in two main topics:

- therapy with beam requires user friendly, low intensity and very reliable machines with an exceptional stability. In terms of energy, the required 230-250 MeV proton beam is easily reached, while for heavier ions (i.e. carbon) figures of the order of 400 MeV/n are required.
- isotope production necessitates higher intensities and sturdy, compact machines.

Future applications like transmutation of nuclear waste, accelerator driven systems or in general very powerful neutron sources aim at a high beam power. Figures are in the range of 10 MW and 1 GeV, mostly for protons or deuterons. Then again, a very high transmission efficiency is vital, along with a very high operational reliability.

Finally, everyone would like to have access to a fast-designed, rapidly assembled compact machine of low investment and operation costs.

3. BEAM DYNAMICS AND HIGH INTENSITY OPERATION MODE

Two events seem to have strongly pushed upwards a significant evolution of beam dynamics in cyclotrons:

- a) the rejection of the ion source out of the cyclotron: ECR source with axial injection for compact cyclotrons, radial injection for separated sector cyclotrons.
- b) the race to higher intensities, whether for proton beams dedicated to deliver high neutron fluxes (PSI), or for heavy ion beams to generate exotic beams either by fragmentation of the projectile or by the ISOL method (GANIL).

Concerning the first point, when the source is inside the vacuum chamber, with a wide spectrum of charge states pulled out of the chimney by a time-varying electric field, only approximations permit the designer to simulate the beam behaviour up to the extraction.

system Measurements of the beam properties during acceleration are imperfect and sometimes impossible Rejecting the ion source outside the cyclotron (apart from other advantages that will be investigated in the next paragraph) makes possible the knowledge of the initial conditions for properly computing this beam behaviour It is not only possible to measure the beam properties (radial and longitudinal emittance, energy spread) before injection, but one can in addition prepare the beam in order to adapt it in the 6-dimensional phase space to the acceptance of the cyclotron this is achieved with slits, bunchers, dipoles and quadrupoles [1]

As for the second point, the race to very high intensities and the consequences on the difficulty to properly extract the beam induced a more and more sophisticated investigation on the behaviour of the particles in the presence of space charge forces In this respect, a tribute must be paid to the PSI group (W Joho, S Adam, Th Stammbach) who made clear concepts that were ignored before Some examples are

- the effect of the neighbouring bunches on the shape and apparent width of the last bunch before extraction A simple model by W Joho predicted that the maximum beam current that can be extracted from a cyclotron is roughly proportional to the third power of the average energy gain per turn This is illustrated in figure 1 for the proton beam in the ring cyclotron at PSI Similarly for heavy ions, a voltage jump from 160 to 200 kV on the dees of SSC2 at GANIL boosted the extracted beam from 5.5 to 9.1×10^{12} pps [2]
- the possibility, at least in compact cyclotrons, to inject a beam with such conditions that its lateral dimensions become equal after a few turns, thus forming a sphere with constant radius This is illustrated in figure 2 A consequence of paramount importance is that the phase length of the bunches reduces as acceleration proceeds This is the so-called “round beam effect” and it is so efficient that in the PSI Injector 2 cyclotron, not only could the flat-top cavity be turned-off, but this cavity could be used to further increase the energy gain per turn through the V^3 effect mentioned above [3]
- space charge compensated bunching [4], an effect that shows up when very high intensities are bunched previous to injection This is illustrated in figure 3 which shows the influence of the DC beam current on the relation between energy spread and phase in the “hot spot” of a bunched beam In the case of a space charge dominated beam, the energy spread is reduced and more beam is contained in the indicated acceptance area of the cyclotron This effect could be very beneficial for a prospective high intensity injector

Other devices can be used to obtain phase compression For example, on the 500 MeV cyclotron at TRIUMF, an auxiliary 4th harmonic RF cavity (the so-called “RF booster”) provides a radial gradient which in turn gives rise to a magnetic time-varying field 90° out of phase with the accelerating field A proper adjustment of the phase difference between the fundamental and the 4th harmonic generates a positive radial gradient which compress off-phase particles longitudinally, as shown on figure 4 [5]

Precise evidence of most of these theoretical advances are hard to establish and more attention must be paid to improvements of the measuring techniques Especially, the particle distribution within the bunches remains a critical unknown and makes accurate prediction difficult

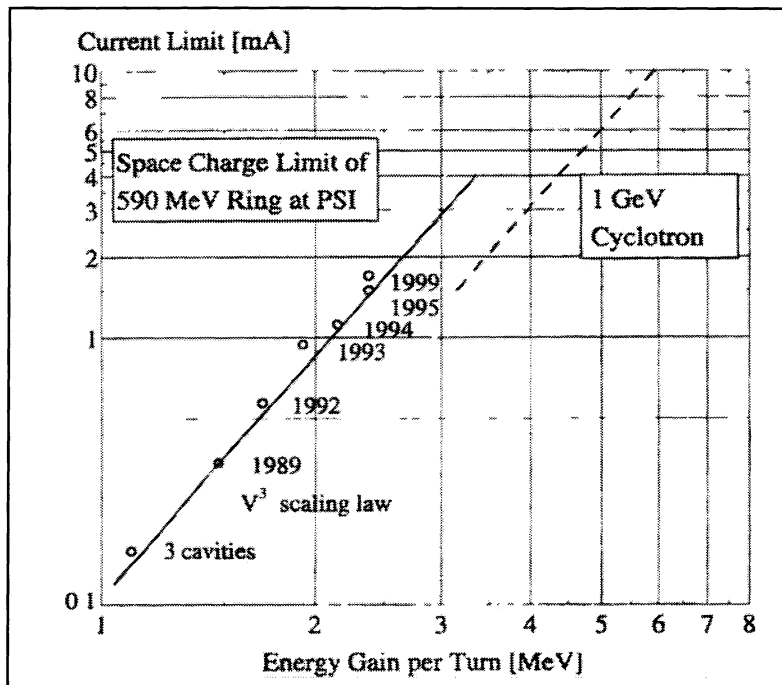


Figure 1 The observed maximum beam current extracted from the PSI Ringcyclotron in function of the average energy gain per turn as established during the upgrade of the cavity voltage. The solid line is the dependence expected if the limitation is due to longitudinal space charge. The dashed line is the extrapolation to a tentative facility with a 1 GeV, 10 mA cyclotron (from [3]).

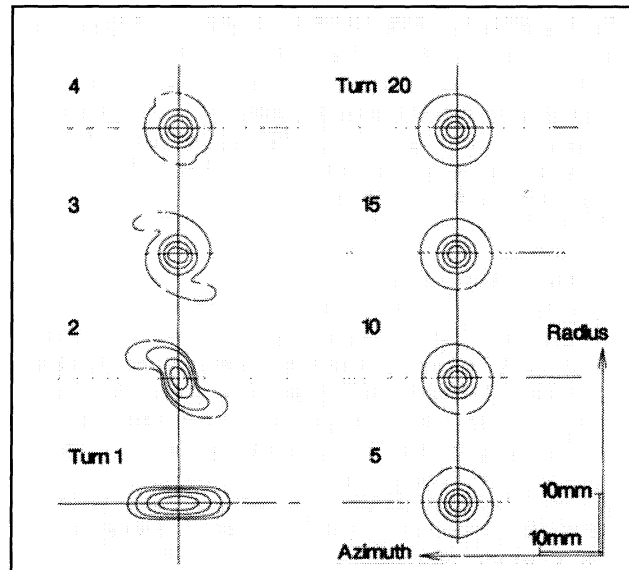


Figure 2 Simulation of the deformation of a cyclotron beam bunch under the influence of longitudinal space charge forces. The case considered is an accelerated bunch with a 1.5 mA beam current starting with a phase width of 15° in the PSI Injector 2. Shown is the projection of the initial bunch and its deformation over the first 20 revolutions.

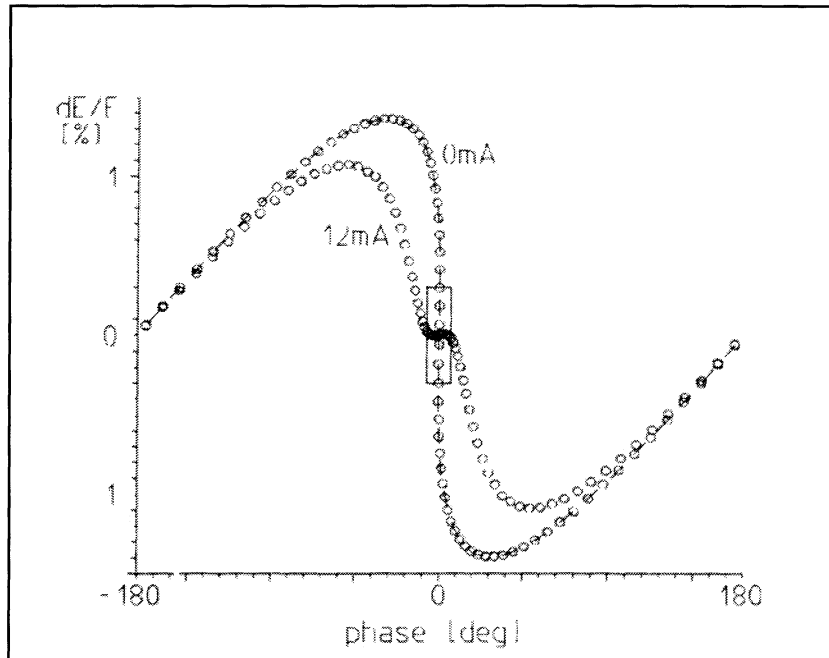


Figure 3 influence of the DC beam current on the relation between energy and phase in the hot spot of a bunched beam. In the case of a space charge dominated beam, the energy spread is reduced and more beam is contained in the indicated acceptance area of the cyclotron (from [3])

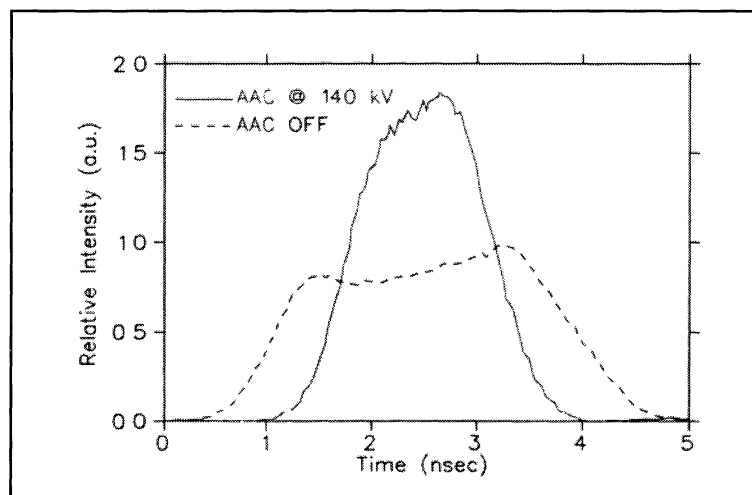


Figure 4 Time structure ($1 \text{ ns} = 8.3^\circ$) of the extracted beam from the TRIUMF cyclotron with the RF booster cavity on and off (from [5])

4. DESIGN OF ELECTRIC AND MAGNETIC CONFIGURATIONS

Two or three-dimensional beam dynamics can only be carried out if the field pattern, both electric and magnetic, is precisely known. Modern codes like TOSCA [6], RELAX3D or CHA3D for magnetic and electric fields provide very accurate maps, especially since they account for the entire configuration. Examples of the accuracy of prediction of these codes are given in figures 5 and 6, both referring to TOSCA. In figure 5, the difference between the computed and measured magnetic field of the CIME cyclotron at GANIL is plotted versus radius for two different values of γ , the relativistic mass increase, it is seen that the difference amounts everywhere to only a few gauss. Figure 6 illustrates the accuracy with which the magnetic gradient in the focusing bars of the K1200 injection channel at MSU [7] could be achieved.

It is not claimed here that field measurements are no longer necessary rather than being used as design tools, therefore necessitating many maps, they become checking tools, controlling once for all the computed configuration.

5. AXIAL INJECTION AND INTERNAL SOURCES

It was suggested previously that the emergence of ECR sources definitely contributed to a better understanding of the internal beam behaviour in compact cyclotrons. In addition, this position external to the vacuum chamber has several advantages:

- it gives more flexibility for design and improvements: insulation, volume, extraction geometry, etc
- it makes tests easier, as they no longer depend on the cyclotron fields (magnetic or RF)
- it allows to take advantage of innovations, i.e. superconducting ECR sources delivering higher intensities of higher charge states, therefore permitting a given cyclotron to overshoot its own performances.

There is however a price to pay for this comfort. Figure 7 is an illustration of what is required to properly inject an ion beam into the GANIL injector with the tools to adapt the 6-dimensional phase space to the acceptance of the machine: the line comprises 4 dipoles, 17 quadrupoles, a double harmonic buncher, one solenoid, 4 pairs of slits, 7 beam profile monitors, two Faraday cups, one current transformer and one inflector. The design of such a line requires extensive computation, especially for the 6-D matching and for the inflector, not to speak of space charge effects to be taken into account. On the other hand, the transmission from the top of the yoke to the exit of the extraction system can be as high as 70%, which represents almost only the RF acceptance of the bunched beam. This is about to be the maximum transmission for a multi-particle, multi-energy compact cyclotron.

The inclusion of an electrostatic inflector is very often a puzzle in terms of limited room or high electric field. It was announced at this meeting by Yves Jongen that a magnetic inflector could come up soon.

On the contrary, for single-particle, single-energy machines like cyclotrons for radio-isotope production or for therapy, it is often easier to leave the source at the centre of the cyclotron, especially since in these cases, the projectile is either a proton or a deuteron (or the corresponding negative ions) and can therefore be produced in large quantities. If the intensity needs to be controlled, a simple electrostatic device like a vertical inflector will do the job. It is only when specific beam quality is required that a set of slits have to be installed to select the proper phase interval in both vertical and radial dimensions, this design can be difficult due to approximate initial conditions. As an illustration, the design of the central region of the PSI Philips cyclotron [8] is a good example.

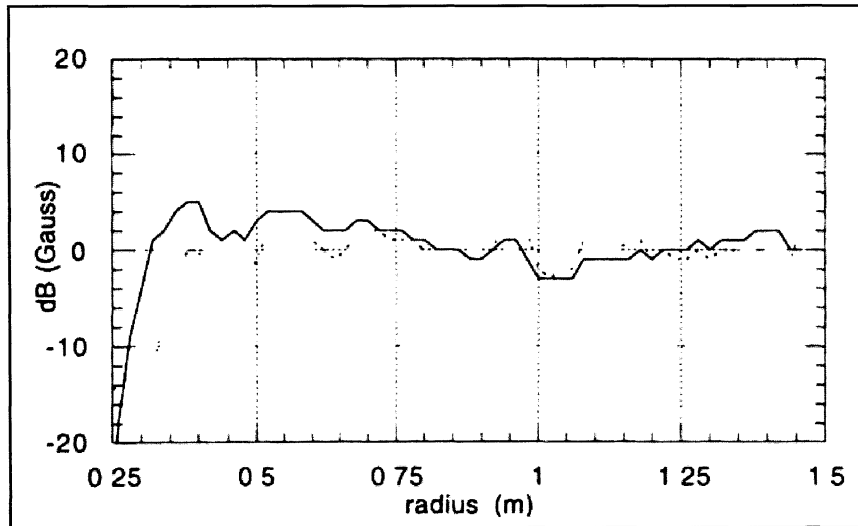


Figure 5 differences between computed and measured magnetic fields in the CIME , the cyclotron of SPIRAL. The two curves correspond to two different values of γ

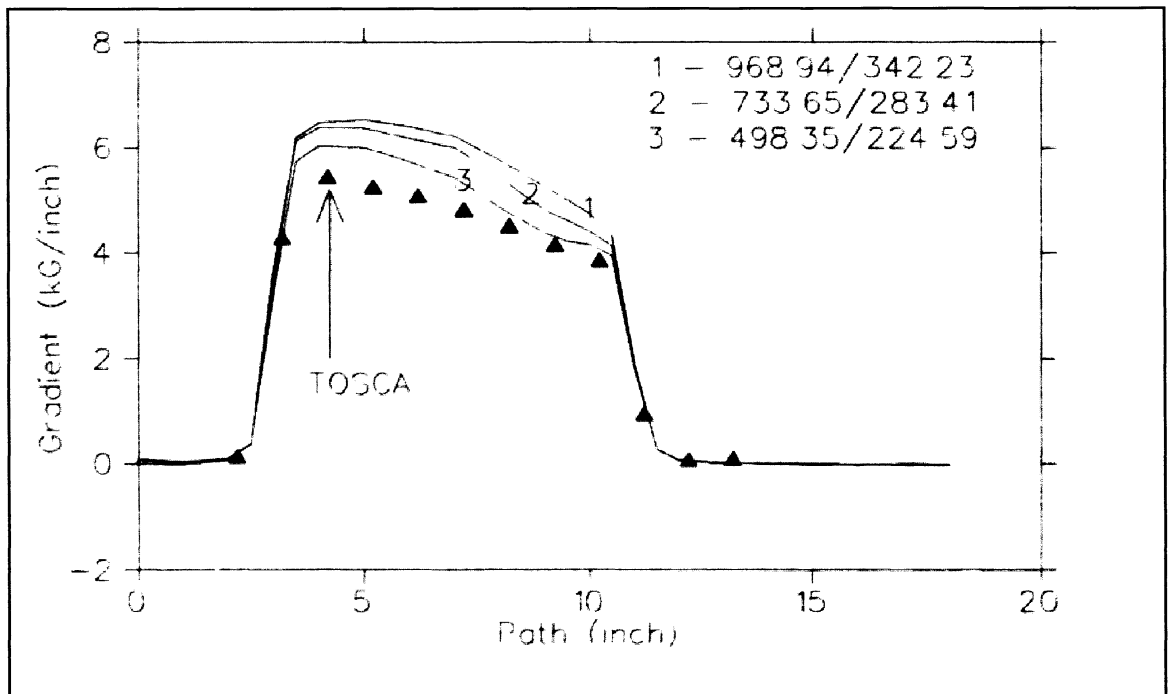


Figure 6 The comparison of the measured and calculated field gradients K1200 injection focusing bars (from [7])

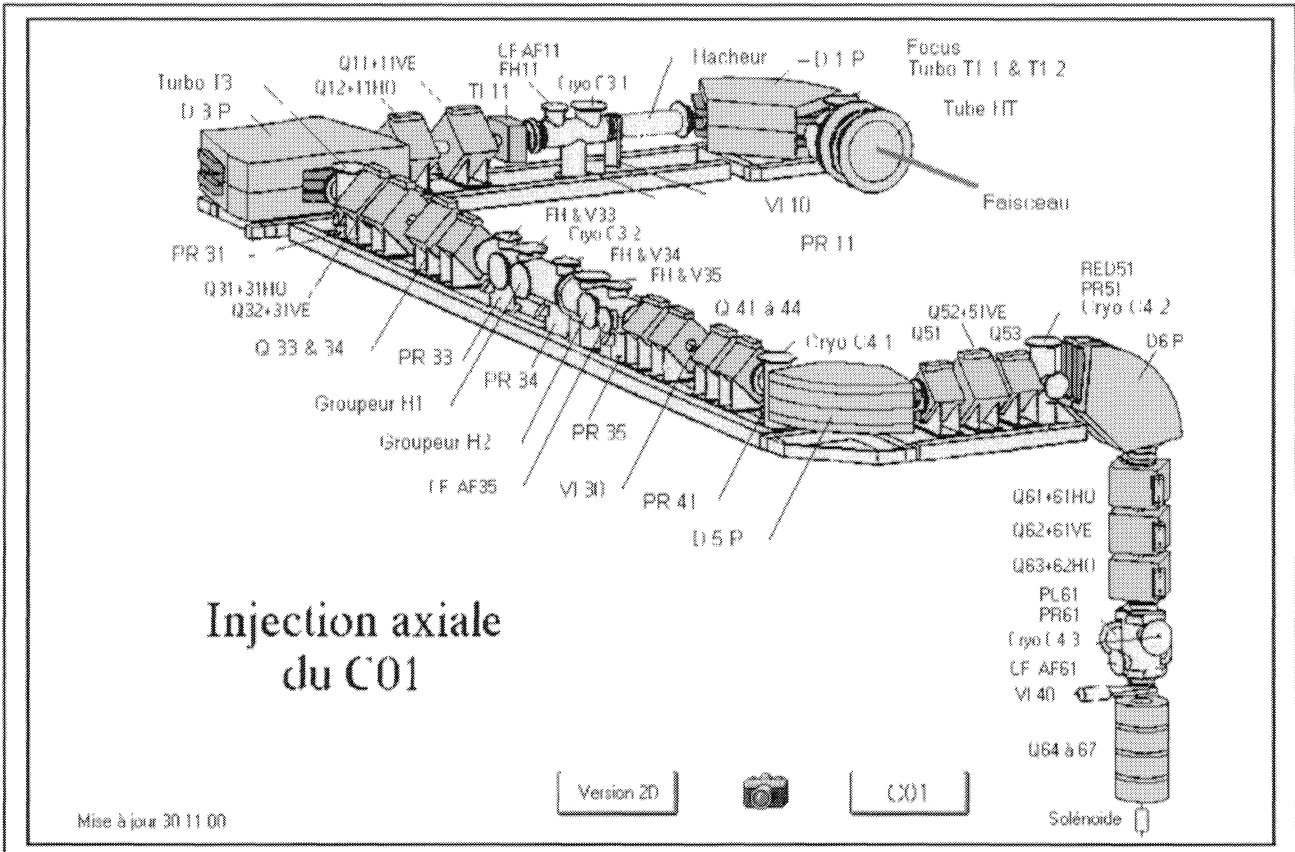


Figure 7 the injection line from the ECR source into the injector cyclotron C01 at GANIL.

6. EXTRACTION

Extracting the beam from a cyclotron seems to be one of the simplest task to achieve it is only necessary to apply a force perpendicular to the trajectory of the last revolution and to focus the beam through the fringing field The device most commonly used is the electrostatic deflector, the main advantage of which being that the septum can be made as thin as possible, thus minimising the fraction of the beam that is inevitably intercepted This method (unavoidable in many cases) is indeed the source of many dysfunctions

- even with low operating voltages (40-50 kV) and in good vacuum conditions, the insulators deteriorate with time, due in particular to metallic vapours generated by sparks along the field lines in the deflector itself or in the accelerating cavities Along the years, a large number of tests with various materials, both insulators and electrodes led only to rather poor amelioration of the long term reliability
- the power lost on the septum limits the value of the internal current due to both activation and thermal problems It was mentioned in paragraph 3 that in order to minimise beam tails and particles in the valleys between two consecutive orbits, the higher the energy gain per turn, the better But a very high voltage on the accelerating cavities is usually not sufficient to separate the last turns in a clean manner , it is in most cases also necessary to induce some resonant motion to the orbits For example, the “natural” turn separation at extraction of SSC2 at GANIL is 3 mm, while by inducing a precession right from injection, this separation becomes 17 mm Nevertheless, the septum (or rather, a water-cooled shield placed in front of it) which is 2 mm thick, gathers several hundreds of watts (figure 8) This shield will be soon reduced to a 1 mm V-shaped tungsten unit, while the copper septum itself will have a thickness increasing from 0.5 to 3 mm In the case of the Ring Cyclotron at PSI , the long range of the 590 MeV protons allows the septum to be made of 50 μm thick tungsten strips (Figure 9)

Whenever possible, extraction by stripping is a very efficient method that by-passes all the problems due both to electrostatics and to the septum thickness It is used in many fixed-field, single particle machines for isotope production as well as at TRIUMF, a 500 MeV, high intensity separated sector cyclotron accelerating an H⁻ beam In addition, adjustable positioning of the stripper foil allows extraction at various energies This process however is limited to swift, light ions for which the stripping efficiency remains close to 100 % or, for higher atomic numbers, to energies low enough not to generate damageable activation inside the vacuum chamber due to the spill beams For example, the extraction efficiency in the U400 cyclotron in Dubna varies from 75 % for a N beam to 20 % for a Xe beam

Finally, it is worth mentioning that, provided the magnetic field of the cyclotron has been shaped in order to show a rapid fall-off near the outer radius of the pole (figure 10), self-extraction has been demonstrated possible [9] This fall-off is given by a groove in one pole, where the (elliptic) gap is small In addition, some coherent motion to push the beam at the entrance of the groove is required An 80 % extraction efficiency was obtained in this manner on a small current H⁺ cyclotron at IBA

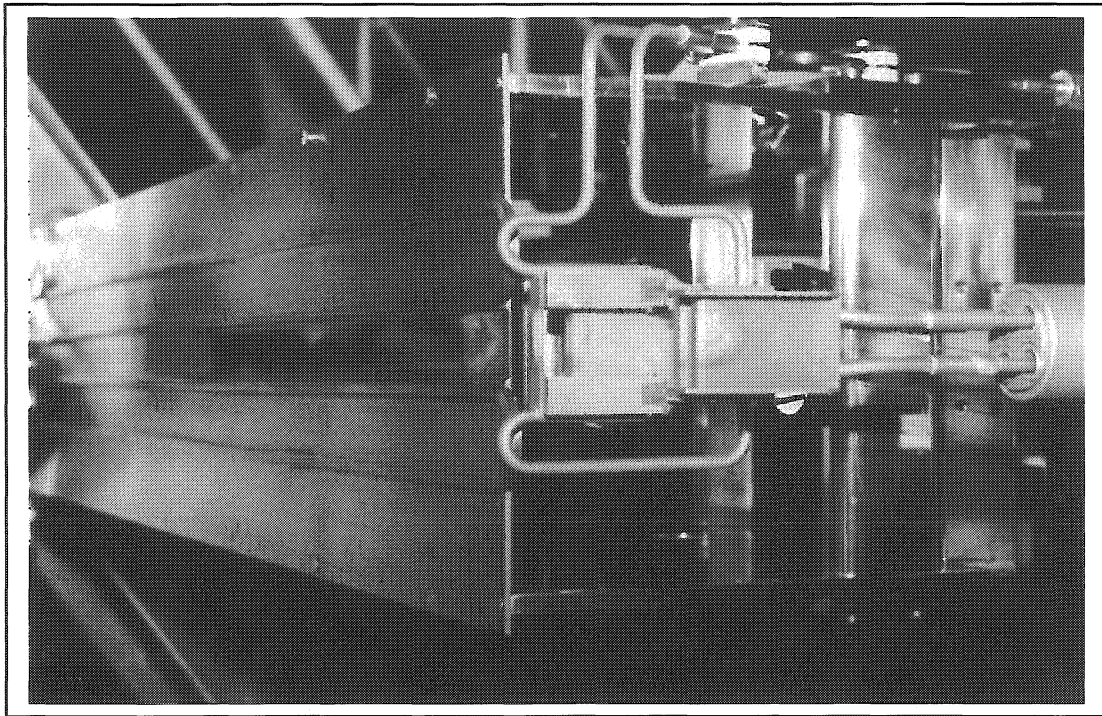


Figure 8 a view of the entrance of the electrostatic deflector of CSS2 at GANIL. The dark surface on the left is the septum, the copper set on the right is the water-cooled shield (pre-septum)

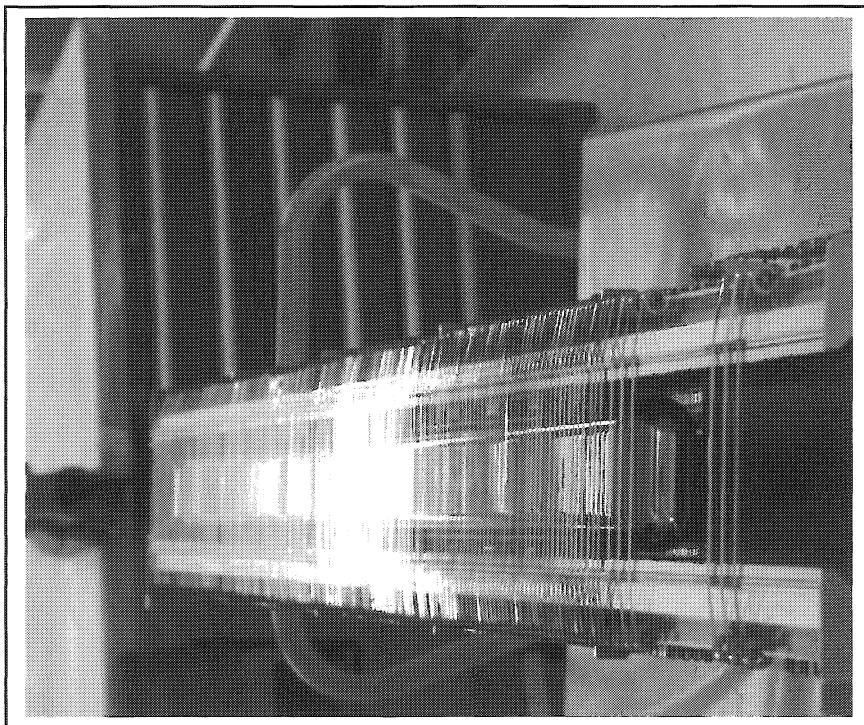


Figure 9 the electrostatic deflector of the PSI Ring Cyclotron (Courtesy of PSI)

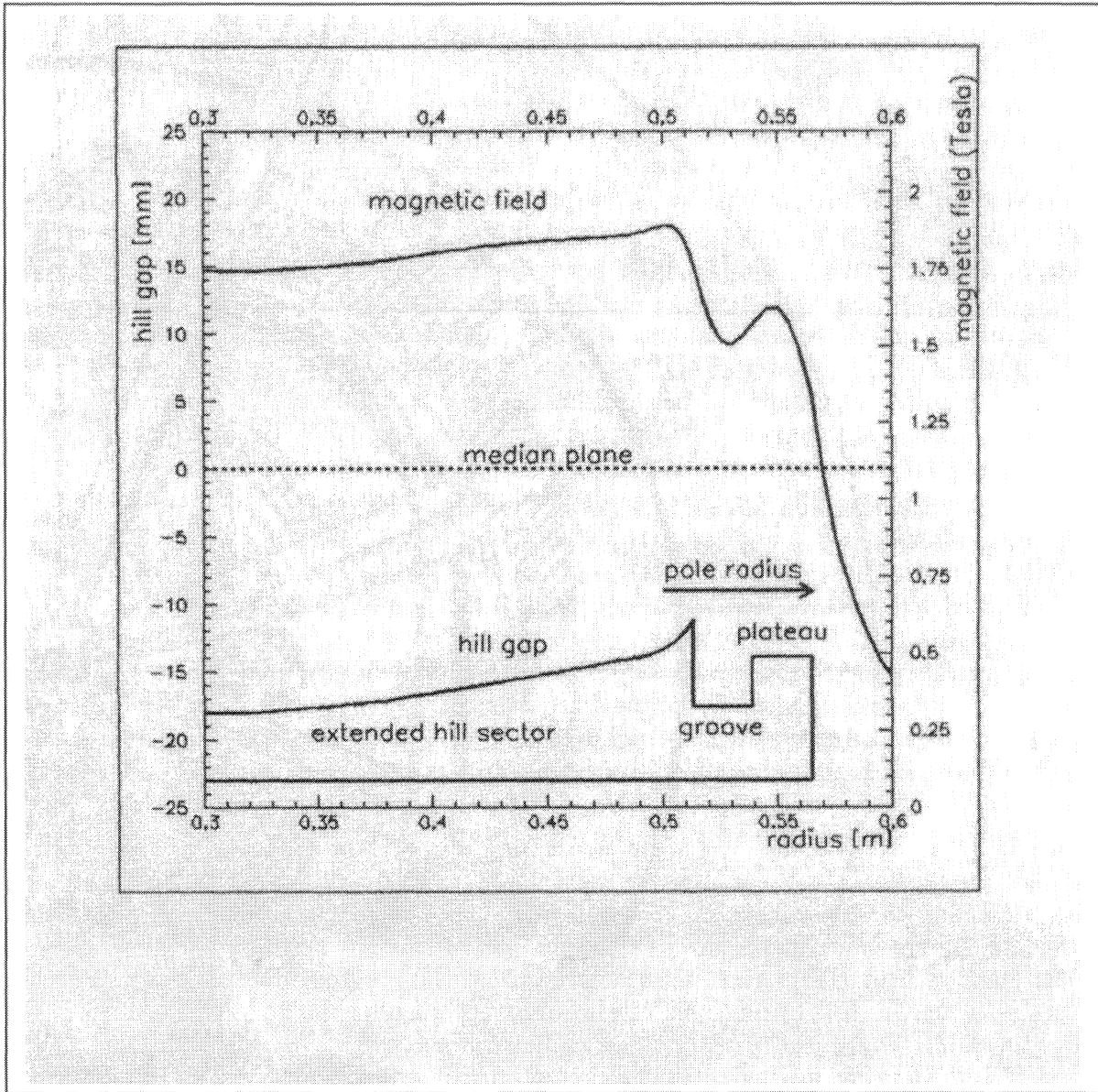


Figure 10 : magnetic field profile in the middle of the extended hill showing the field-dip produced by a groove (The IBA self extracting cyclotron, [9])

7. RESEARCH

Trying to develop the trends in nuclear physics research with cyclotrons would be a formidable task, well beyond the scope of this paper. The only example of radioactive ion beams is sufficient to illustrate the developments to come.

Production and acceleration of beams of short-lived nuclei generated in nuclear collisions between heavy projectiles have received a growing interest. New types of nuclear structures have been discovered, the quest to understand the nucleosynthesis is far from being completed, nucleon distribution in unstable nuclei are accessible and a formidable expansion of the chart of nuclei is open. Cyclotrons all over the world are playing a major role in this field.

As it is well known, these radioactive species can be produced as beams by two techniques:

- the in-flight (or projectile fragmentation) method an intense beam of stable nuclei is accelerated at energies of several tens of MeV/n and passes through a thin target. One of the outgoing unstable species is selected, with a more or less large collection angle, and is used as a beam, but of course with no way to control its energy. At GANIL, this is achieved with a device called SISSI [10]. The energetic beam coming from the cascade of three cyclotrons is very sharply focused through a superconducting solenoid onto a rotating target and the fragments are collected with a large angular acceptance thanks to a second superconducting lens.
- the ISOL (Isotope Separation On Line) technique the radioactive species are produced by completely stopping the high energy, high intensity beam in a thick target. As they stand as neutral atoms in this target, it is necessary to heat it so that they diffuse towards an ECR source for ionisation before re-acceleration. When the post-accelerator is a cyclotron, like in Louvain-la-Neuve, GANIL, Dubna and in a near future, MSU and RIKEN, it is operated not only as an accelerator, but as a high resolution mass spectrometer.

In these methods, the cyclotron has two definite advantages:

- it delivers high intensities with DC operation
- the micro-bunch gives additional identification and separation methods

8. NON-MEDICAL APPLICATIONS

Very few laboratories have a cyclotron uniquely devoted to basic research, studies or measurements in non-nuclear physics. However, places like ISL (HMI Berlin), KFK (Karlsruhe) or JRC-Ispra (Italy) are relevant examples.

There is a wide range of research and applications spread all over the world, and it is sometimes difficult to evaluate the proportion of beam time devoted to each topic and the pace of development. A possible classification is listed below (restricted to cyclotron energies):

- material analysis: wear measurements (automobile industry, pipelines) [11] and corrosion studies (measurements of the severity of corrosion of sea water on metals), monitoring of machine movements in mechanical engineering (balls and cages in ball bearings, inner parts of high speed turbines, piston liners). Germany, USA, Great Britain and Japan are especially active in this field.
- radiation damage studies: simulation of radiation damage in the development of fusion reactor materials (PSI, ISPRA, VEC Calcutta, HIRFL Lanzhou and KfK [12]), Radiation effects on permanent magnets and amorphous metallic alloys (MSU, Jyväskylä, CIRIL/GANIL), on the resistance of semiconductor devices and sensors to space radiation, and optical glasses (ISL, CIRIL)
- basic research in solid state physics (ISL, CIRIL)

- fabrication of microfilters (I.B.I. and JINR Dubna, on an industrial scale)
- modifications of superconducting properties
- determination of the amount of impurities in metals, plastics, rubber and polymers.
- induction of cell lethality, mutations, cell transformation and carcinogenesis by heavy ion beams of several tens of MeV/n (GANIL.)

It must be mentioned that at TIARA/Jaeri (Japan), design studies have been launched for the project of a K900 superconducting cyclotron for research in material science and biotechnology [13]

An industrial application could come from the safety problems in airports for many years, methods are being looking for detecting on line clandestine explosives in passengers suitcases. Nuclear technologies have been especially investigated and in particular, resonant absorption of a pulsed neutron beam is of interest For this purpose, EBCO [14] proposes a compact 9 MeV deuteron cyclotron

8. MEDICAL APPLICATIONS

8.1. MEDICAL IMAGING AND THERAPEUTIC APPLICATIONS

Radionuclide production is certainly the most striking success in cyclotron applications With the development of PET centres, the demand for small, compact, user-friendly accelerators is following a rapidly increasing trend. Figure 11 shows the result of a worldwide survey of the cyclotrons used for this purpose [15] Since then, it appears that this number will have increased by more than 100 in the years 2002-2003 In addition to producing the standard ^{11}C , ^{13}N , ^{15}O , ^{18}F , ^{123}I and ^{203}Tl , about 50 radiopharmaceuticals are required, including ^{64}Cu , ^{103}Pd and ^{186}Re for therapeutic applications

8.2. THERAPY WITH BEAMS

Only a few cyclotrons in the world are designed and used for the unique goal of therapy Most of the cyclotrons have to spare time with other applications and research. This is the case at NAC (RSA), PSI, ISL, TRIUMF and Uppsala

For an hospital-based machine, the requirements are set by the specific operational and safety needs of a medical facility high beam stability, high availability and reliability, simple operation and robust design

Two synchrocyclotrons have been reconverted to full time operation for therapy the Harvard University (USA) 160 MeV machine and the CPO (Orsay) 200 MeV The 200 MeV proton cyclotron facility at Bloomington (Indiana) is also being reconverted and a medical facility added

Full time operating proton cyclotrons are Clatterbridge (UK) and CAI (Nice, France), both of them mostly from the treatment of eye melanoma, the superconducting machine at Harper Hospital, Detroit and Seattle (U of Washington) for neutron therapy and the IBA C235 at NPSCT Boston

Two new projects are in the design period

- PROSCAN at PSI [16], a dedicated proton superconducting cyclotron (collaboration with ACCEL., NSCL and KVI)
- A 400 MeV/n superconducting cyclotron for light ions with charge-to-mass ratio 0.5 at NSCL/MSU [17]

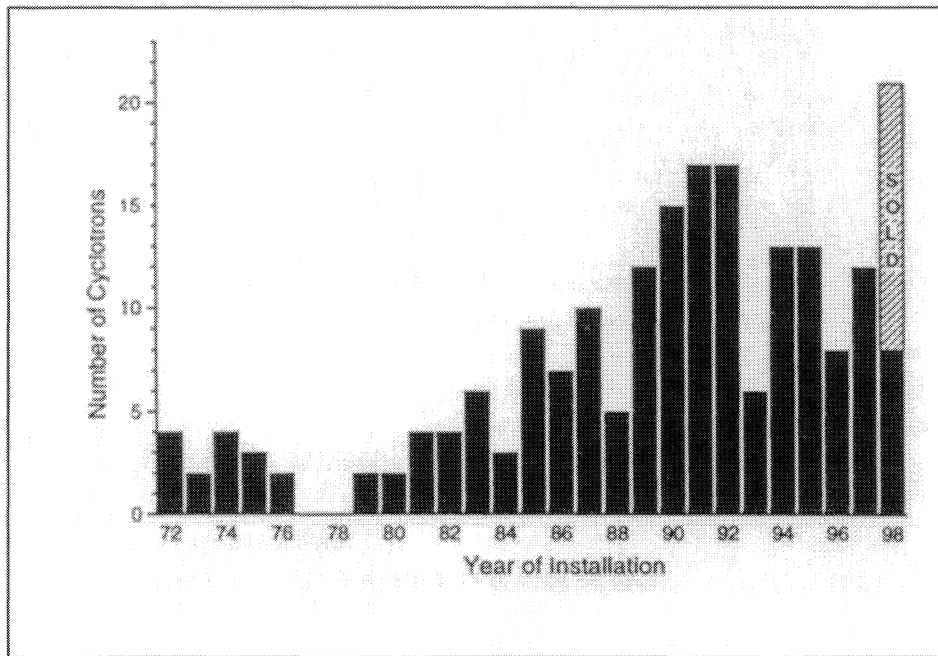


Figure 11 . number of cyclotrons commissioned since 1972 (from [14])

9. TOWARD VERY HIGH POWER CYCLOTRONS

New applications of particle accelerators appeared in the last decade, mostly turned to solve middle-term problems linked to the production of energy. The so-called “energy amplifier” proposed by C. Rubbia and collaborators [18], similar schemes to burn radioactive waste by transmutation, or inertial fusion programs require high beam power in the range of 1-100 MW. Demonstrators for such applications have had requirements varying along time since the initial proposals and the present 1-10 MW needed for a first step are well within the possibilities of cyclotrons. However, a very stringent constraint is put on the beam stability: there should be no more than a few tens of (short, i.e. 1 second) beam interruptions *per year*.

PSI has demonstrated its capability to accelerate and extract with practically no loss a 590 MeV, 2 mA proton beam with the Ring Cyclotron. About 8 years ago, the expected power for an experimental accelerator driven system (ADSX) was 10 MW, and the PSI group answered by proposing the “dream machine” [19] shown in figure 12. It is a room-temperature, 12 sector cyclotron with 8 RF cavities (1 MV peak voltage). The over-all diameter would be 16 m. The injected 120 MeV proton beam is brought up to 1 GeV in 140 turns. It is to be noted that, if higher power were required, several such cyclotrons working in parallel would be a solution to insure a better average stability of the resulting beam on the target located in the reactor. Recently, a more modest goal is aimed at in the TRADE project, namely a 115 MeV, 2 mA machine, which in fact accelerates singly ionised molecular hydrogen atom up to 230 MeV with an extraction by stripping [20]. The AIMA company proposed this superconducting solution, only 5 metres in diameter (figure 13).

For MYRRHA (a sub-critical reactor for multipurpose neutron physics research, IBA studied a room-temperature cyclotron (19 m in diameter) and a superconducting solution, both for a 700 MeV H_2^+ beam.

It is clear however that, in this field of high power accelerators, linacs although more expensive than cyclotrons have the advantage of scalability towards the 40 MW region.

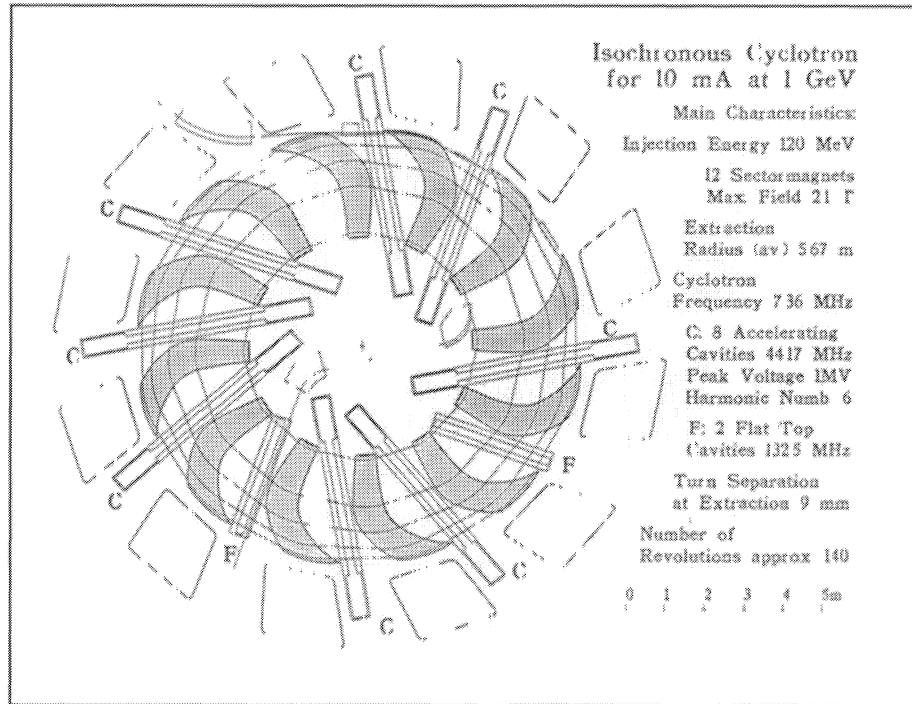


Figure 12 conceptual layout of of a high power cyclotron for 10 mA current at 1 GeV (“dream machine”) There are 8 accelerating cavities (C) and two flat-top cavities (F) From [18]

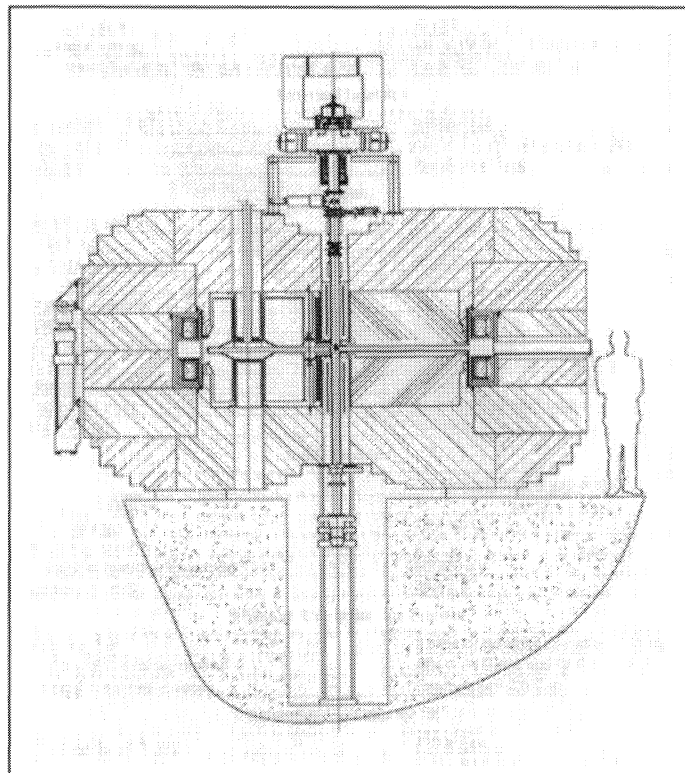


Figure 13 Vertical cross-section of the AIMA-115 N Superconducting cyclotron (from [19])

10. FFAG ACCELERATORS

The Fixed-Field, Alternating Gradient (FFAG) accelerator is an old idea dating back to the fifties [21]. Due to the enormous cost of linacs above the GeV level as well as the amount of steel that would be necessary for a cyclotron (at that time, superconducting cyclotrons did not exist), an accelerator in the form of an annulus was proposed for high velocity particles. There is another reason why a more-than-1-GeV cyclotron would be difficult to design while there is in principle no limit on the energy of an isochronous cyclotron, it may be shown that for stability reasons, the number of sectors must increase with the output energy and even though, the number of serious resonances that the operating point would be crossing is increasing also. One GeV may be taken as a good order of magnitude for a limit. Therefore, the idea came up that one should design the magnetic field pattern of the annulus in such a way that the operating point in the betatron tunes (ν_r, ν_z) plot remains almost fixed. It follows by simple considerations that isochronous operation is impossible and therefore that the RF frequency must be modulated.

A complete lecture on the principles of FFAGs is beyond the scope of this paper. However, some properties are listed below, from which one can draw the advantages and drawbacks of such a concept. In FFAGs .

- the sectorized pattern is similar to separated sector cyclotrons, with an empty core.
- each sector, spiralled or not, is composed of a bending section with focusing/defocusing
- the magnetic field pattern is time-independent, but basically non-linear and therefore, complicated to design
- the range of frequency modulation is somewhat less than in a synchrocyclotron the RF frequency first rises up to the transition energy, then decreases
- the electric frequency does not have to track changing values of the magnetic field, so that tuning on almost any frequency schedule is in principle possible (high repetition rates, short acceleration time)
- any particle is free to seek the radius at which the average field is correct for its momentum (large acceptance)
- stacking is possible
- although wider than in a synchrotron, the vacuum chamber is of limited radial size as compared to an isochronous cyclotron

Only electron models were built in the fifties by the MURA group. The resurrection of the FFAG principle originates in several needs for accelerators:

- high energy (> a few GeV), high intensity machines
- fast accelerating cycle for short lived particles (muons, radioactive ions, etc) and large acceptance

Therefore, in 2000, KEK designed a proton model (0.5 MeV, 1 kHz repetition rate) as a proof of principle and it was put in operation [22]. In addition, the construction of a 150 MeV proton FFAG was approved in Japan in the same year. It is intended to serve for proton therapy as well as as a model for a muon accelerator (20-50 GeV) generating intense neutrino fluxes. At BNL, Takahashi [23] proposes an induction FFAG to drive a sub-critical reactor.

Although not cyclotrons (and not really synchrotrons either), FFAGs might bring elegant solutions in the field of high power beams.

11. SUMMARY

Although such a rapid survey cannot be exhaustive, some trends in the evolution of the cyclotron may be detected

- beam dynamics supported by a better knowledge of initial conditions and better measurements is becoming more accurate
- the evolution of ions sources allows better performances of cyclotrons in terms of intensity, energy and beam properties
- the number of cyclotrons for PET is exploding
- cyclotrons are still in the race for an ADS demonstrator
- FFAGs are making a come-back after a 50 years absence

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